Human Head Modeling and Personal Head Protective Equipment: A Literature Review

Jingzhou (James) Yang[1], Jichang Dai[1], and Ziqing Zhuang[2]

[1] Department of Mechanical Engineering, Texas Tech University, Lubbock, TX79409, USA
[2] National Personal Protective Technology Laboratory, NIOSH, Pittsburgh, PA 15236, USA
james.yang@ttu.edu

Abstract. Human head is the most important but fragile part of human body. In order to design the head-gear and study the sophisticated capabilities of human head, the head models have been developing for decades. There are two types of human head models: digital headform and finite element model (biomechanical head model). The complexity of head structure makes these attempts very difficult until the invention of the high-speed computers and the modern medical devices like computed tomography (CT) or magnetic resonance imaging (MRI). Head modeling also has widely potential use in the design process of personal head and face protective equipment (PHFPE). Hazards of processes or environment, chemical hazards, radiological hazards, or mechanical irritants are encountered daily for workers. Those hazards are capable of causing injury or illness through absorption, inhalation, or physical contact. PHFPE includes helmets, masks, eye protection and hearing protection. This study attempts to review different kinds of head models and PHFPE, such as respirators, helmets and goggles. It mainly focuses on the historical developments.

Keywords: Headform; biomechanical model; respirators; helmets; goggles.

1 Introduction

Head injuries and facial damages are one of the main causes of death and physical disability. The incidence (number of new cases) of head injury is 300 per 100,000 per year (0.3% of the population), with a mortality of 25 per 100,000 in North America and 9 per 100,000 in Britain. In most of countries in the world, workers, athletes and people exposed in a hazardous environment are mandatorily asked to wear personal head protective equipment. Respirators, helmets and goggles are the three most commonly used ones. How to design and test them efficiently is a great concern for both manufacturers and customers.

However, now the companies mainly rely on the experimental way to verify the design. This method is costly and does not have enough flexibility. Moreover, the procedures of the tests differ from one standard to another. So, digital simulation will be a good alternation or at least a necessary correction for experimental laboratory testing. With a digital head model, the manufacturers are able to test their products on a virtual human body, to check the comfort level and simulate different environments that may not be possible using experimental tests.

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Intending to develop a low-cost alternative to the experimental test method, many head models have been proposed for the past 30 years. There are two types of head models: digital headform and finite element model. NIOSH uses Sheffield headforms to conduct respirator certification testing; the National Operating Committee on Standards for Athletic Equipment (NOCSAE) uses headforms created from anthropometric measurements of army aviators published in 1971 (NOCSAE, 2007); and the American National Standards Institute (ANSI) and the American Society for Testing Materials (ASTM) follow ISO/DIS6220:1983 for headforms (ANSI, 1997; and ASTM, 2002). The occupational and educational eye and face protective devices standard (ASTM, 2003) uses the Alderson 50th percentile male headform which is based on Health Education and Welfare data collected in the 1960s (First Technology Innovative Solutions, Plymouth, MI). Many other headforms used for certification testing in the United States are also based on anthropometric data collected over 30 years ago. Zhuang and Viscusi [34] developed the first surface-based 3-D headform for respirator fit testing using the date collected recently.

Most of the other models belong to finite element models. FE models contain the anatomical structures of the human head. In the early models, due to the technique limit, they only use the simplified and regular geometry of the head. Recently, more complicated models have been developed that include more external and internal details of the head. The Hardy and Marcal [9] developed the first finite element model in 1971. Their skull-only model was then improved by Shugar [23]. He decided to treat the brain as kind of fluid. Then a more realistic model was developed by Nahum et al. [17] where the brain is modeled by means of 189 eight node brick elements and a linear-elastic behavior has been adapted to tissue mechanical properties. A well-known model called WSUBIM (Wayne State University Brain Injury Model) was developed by Ruan et al. [21] where the number of nodes is increased to 6080 and elements to 7351. These numbers were again raised to 17656 nodes and 22995 elements by Zhou et al. [33]. The FE head model has been improving all the time, to name a few: [14, 16, 30, 31, 35]. Two sets of experimental data are commonly used to valid the FE models [17, 25]. But with the rapid development of computer technology, researchers now can use more detailed properties to model their FE models, and achieve good consistency with the experimental data [27, 28, 29, 30, 35].

In this paper, we first introduce the basic concept of head and face anthropometry. Then, different head models are reviewed in Section 3. In Section 4, we review the detailed PHFPE such as respirators, helmets, and goggles. Section 5 will summarize digital head models and PHFPE and give conclusion.

2 Head and Face Anthropometry

Anthropometry, in physical anthropology, refers to the field that deals with the physical dimensions, proportions, and composition of the human body, as well as the study of related variables that affect them. Nowadays, to optimize the products in industrial design, clothing design and ergonomics where statistical data about the distribution of body dimensions in the population is needed, anthropometry became more and more critical. There are fifty three key parameters in human head and face [7]. In order to acquire the anthropometric measurements described above, a series of landmarks on the subject's face are chosen [1]. For traditional measurements, spreading and sliding calipers and tapes are used. But when it comes to the 3D scans, it may be a problem because some bony landmarks are not as readily apparent without palpation.

3 Head Modeling

In the past several decades, many test head models have been used in all different experiments for various purposes. Digital head models play an important role in simulation environments related to head injuries or head protection equipment assessment. This section will summarize digital headform and FE models.

3.1 Digital Headform

The types of headform vary from standard to standard. Since the headforms need to represent the anthropometry of a specific region, different countries developed their own headforms. The digital headform is the numerical model of the physical headform. There are many physical headforms, but few of them are digitized. In this section, we only introduce the digital headforms developed in U.S.

In 1994, Reddi et al. [20] reported three types of headforms (small, medium and large) used in military ejection seat as well as fit assessment of helmet and other head-supported equipments. The geometries of these headform are obtained from U.S. Army Anthropometric Survey. Creation of these three digital headform designs was accomplished using the AutoCAD computer-aided design package. A total of 48 linear head dimensions were used to locate the positions of 26 facial landmarks. A headform wireframe was created through the facial landmarks from a system of spline entities. The AutoSurf surface modeling system was then used to generate surfaces between closed sections of the headform wireframe.

To access fit test for respirators, Zhuang and Viscusi [34] developed a surface-based headform model in Fig. 1. A Cyberware rapid 3-D digitizer, with its associated computer and data processing software, was used to scan 1,013 subjects (713 male and 300 female). A Class I laser was projected, in a thin line, onto the subject and followed the contour of the face and head during a 360 degree scan. Additional processing and measurement of the images was accomplished using Polyworks. The criteria for choosing an individual 3-D head scan was based on calculations of principal components one and two (PC1 and PC2).

3.2 FE Model

There has been a long history about FE modeling and analysis of human head for understanding of the biomechanics and mechanisms of head injury. Voo et al. [26] made a comprehensive review of FE models. The basic trends of the development of FE models are:

1. *From simplified model to detailed model*. Early idealized model had simplified and regular geometry such as a spherical or ellipsoidal shell for the skull [9] that concluded only the skull. The skull was then idealized with a double curved and arbitrary triangular shell element. Shugar [23] published his 2D FE headform model. The skull is represented as a closed rigid medium. The membranes are not

included in the model, and brain was assumed as an elastic material but not a visco-elastic one. He also assumed the brain is firmly connected to the skull. And the scope and limitations imposed by this assumption of linearity are discussed in this model. Khalil and Hubbard [11] used a closed oval shell to simulate the human skull. The scalp was modeled as an encased elastic layer. The intracranial contents were represented by an inviscid fluid. Then these simple models were developed based on anthropometric and anatomical data, more structures were included. Like the Horsey and Liu's model [10]. It is the most comprehensive FE model of human head and neck in 80's. This model included one half of the head and neck in the saggital plane. It took into account the gross neuroanatomy as well as the inertial and material properties of the head and neck. It studied the response of a head-neck model subjected to occipital load, but the importance of the membranes of the brain and the neck was not discussed. Wayne State University Brain Injury Model was developed by Ruan et al. [21]. The brain, skull, and CSF were developed as eight-noded hexahedron elements simulating the actual anatomy of the skull and brain. The scalp, dura mater and falx cerebri were represented as four-noded thin shell elements. Kumareasan et al. model [14] was constructed very realistically due to the development of computer science. The preprocessor of a finite-element package NISA (Numerically Integrated element for System Analysis) was used and the free-vibration and transient analyses were carried out. It contained almost all actual geometry of the different parts of head, including the skull, CSF, falx cerebri, brain, tentorium cerebella and the neck. With the development of computed tomography (CT) or magnetic resonance imaging (MRI), researchers have been able to acquire accurate and real time images for modeling [2, 29].

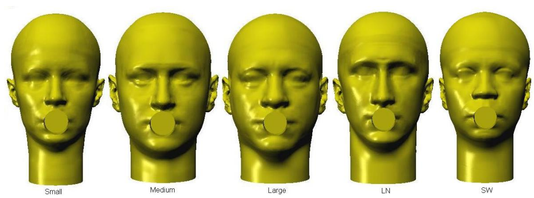

Fig. 1. Small, medium, large, long and short digital headforms

2. *The total number of nodes and the elements gradually increased.* In Nahum's model [17], the brain was modeled by only 189 eight node brick elements. Then Ruan et al. [21] increased the elements to 7351 and nodes to 6080. In King's models [12], there are 7205 nodes and 9146 elements. In Zhou et al. Model [33], it contains 17656 nodes and 22995 elements. Zhang [32] developed two models that included 17656 nodes, 22995 elements and 226000 nodes and 245000 elements, respectively.

Within FE models, there are 2-D and 3-D models. 2D models are useful for parametric studies of controlled planar motions and simplify the inclusion of geometrical details. But when it comes to large deformations and the impact and inertial load analysis, because of the low shear resistance and large bulk modulus material exchange between regions is likely to occur, these problems can only be described by 3D models. Bandak et al. [2] developed a 3D modelthe using CT scan images. But such procedure requires CT scans of the geometry, so it has limitations if one need an average models. Also this technique that automatically generates a FE model of complex geometries has issues in creating a well conditioned element mesh. Kumaresan et al. [14] developed another approach that has more flexibility. He used the upper limits of the landmark coordinates of the external geometry of a head, and then divided the head to 33 layers in the horizontal plane. The coordinate of the curves are connected to the exterior landmarks. Values of all the points were inputted into a FE package to generate the models. [3].

4 Personal Head and Face Protective Equipment

Personal protective equipment, or PPE, includes a variety of devices and garments such as goggles, coveralls, gloves, vests, earplugs, and respirators. The OSHA standards [8] that deal with personal protective equipment consist of different requirements. This section describes three typical head and face protective devices such as respirators, goggles, and helmets in the literature.

4.1 Respirators

Respirators protect workers against insufficient oxygen environments, harmful dusts, fogs, smokes, mists, gases, vapors, and sprays, and these hazards may cause cancer, lung impairment, other diseases, or even death.

There are two main categories of respirator: the air-purifying respirator and the air-supplied respirator which can supply an alternate source of flesh air. The former can then be divided to another three kinds: (1) Negative-pressure respirators, using mechanical filters and chemical media. (2) Positive-pressure units such as powered air-purifying respirators (PAPRs). (3) Escape only respirators such as Air-Purifying Escape Respirators (APER) for use by the general public for Chemical, Biological, Radiological, and Nuclear (CBRN) terrorism incidents.

The first full and half facepiece respirator test panel was developed by the Respirator Research and Development Section of Los Alamos National Laboratory(LANL) under demand from National Institute for Occupational Safety and Health(NIOSH).This panel is known as LANL respirator fit test panel. Three different fit tests are summarized as follow:

(a) *TIL test*: Here is how the NIOSH Total Inward leakage Test (TIL Test) for Half-mask Air-purifying particulate Respirator been conducted. The respirator will be tested on 35 human subjects, having facial sizes designed by the respirator manufacturers for the specific facepiece, from a NIOSH panel having facial sizes and shapes that approximate the distribution of sizes and shapes of the working population of the United States. The actual TIL value shall be recorded in accordance with the PortaCountTM instructions, for each test subject while performing the following sequence of exercises for 30 seconds each, showed in pictures below. Normal Breathing, Deep breathing, Turn head side to side, up and down, recite a passage, reach for the floor and ceiling, grimace and normal breathing. This test will measure the concentration of a challenge aerosol outside of the respirator and that within it.

(b). Irritant Smoke Fit Testing: This qualitative respirator fit test is conducted by directing the smoke stream from ventilation smoke tubes (intended to study building ventilation systems) at the respirator face seal. The involuntary nature of the reaction is the reason many prefer this test over other qualitative fit tests [4].

(c). Saccharin qualitative fit testing: This test is conducted with an inexpensive, commercially available kit that challenges the respirator wearer with a sweet tasting saccharin aerosol. After previously having been screened to assure that he/she can taste saccharin at the required concentration, the respirator wearer is asked to report if saccharin is tasted during fit testing. If so, the respirator is considered to have an inadequate fit and fails the fit test [4].

4.2 Helmet

The history of helmet can be traced back to Ancient Greek and China, when the warrior wears leather hat to protect them from the wound of sword and arrow. Helmeted motorcycle riders have a 25% percent lower fatal rate compare to the un-helmeted riders [24]. Although helmet had been used for more than thousand years, the systemic study of its function and mechanism only appear recently in 1940's, when the English researcher Cairn [5] reported a study of motorcyclist fatalities, established the value of crash helmets. In the United States, helmet development was pursued mostly by the military, and then came to the Sports Car Club of America (SCCA). In 1961, the American Standards Association (ASA) established a committee for protective headgear. The first ASA helmet standard was published in 1966, which was named: Z 90. 1-1966. Protective Headgear for Vehicular Users. Its first revision was published by ANSI in 1971. The supplement, ANSI Z90. 1a-1973 was released in 1973 to correct a technical error.

There have been so many different systems for performing helmet impact tests since the 1940's. Snell Memorial Foundation, established in 1957 as the most authoritative helmet standards setter in US, says "Standards differ in many ways from country to country, and for different applications.

Because of the different standards, so there are many different helmet test systems. And for the different types of helmets, the test procures are not the same. The same thing is, they all use physical headform to conduct the impact test. There are quite a number of impact test headforms. The two most commonly used in the United States are those from the DOT motorcycle helmet standard FM VSS 218 and ISO DIS 6220-1983. These experimental tests are costly and have limited flexibility. So many researches now focus on the finite element modeling of the helmeted headform. However, simulation of helmeted headform is not simple. That is because of the complexity of human head. For instant, for an impact simulation of solid metallic or wood headforms, it is easy, but after you put the skull, membrane and brain properties into your consideration, that is a very complex problem. Fortunately, with the rapid development of computer calculation capability and finite element method, researchers now are able to develop more realistic digital models to simulate the impact test of helmet. To name a few here: Shuaib's research [22] on motorcycle helmet crash studies from biomechanics and computational point of view. So is Kostopoulos [13], he also selected motorcycle's helmet as the subject, but from different view: A parametric analysis had been performed to study the effect of composite shell stiffness and the damage development during impact. Mills [15] chose bicycle helmets to make oblique impacts with a road surface. In Pinnoji's paper [19], his finite element models of the head and helmet were used to study contact forces during frontal impact of the head with a rigid surface. Not many digital helmeted headforms are studied. This aspect is still under gradual progression.

4.3 Safety Goggle and Spectacles

Safety goggle or spectacles is a form of protective eyewear that usually encloses or protects the eye from being stroke by particulates, water or chemicals. According to the Bureau of Labor Statistic (BLS), there are estimated 1000 eye injuries in US every day, and more than $300 million dollars loss in medical expenses per year. BLS found that 60% of workers with eye injuries were not wearing safety goggles. Second, even within these one wearing goggles, they are not wearing it properly. In a word, only 6% of workers who is suffering potential eye injuries wear goggles [6]. Depending to the working environments, properly goggles should be chosen as below:

4.3.1 Test of Goggle or Glasses

The new ANSI Z87.1-2003, which is instead of the old ANSI Z87.1-1989) sets the new requirements that goggles should meet. The old 89 standard only concerns about the ability of the frame of the safety goggle to withstand the High Impact Testing, but now the new standard extents it to both frame and lens. Lens now has two levels of performances, Basic Impact and High Impact. If the lens passes the High Impact testing, thinner thickness will be accepted. But if the lens does not meet the High Impact Testing, a warning label should be attached to indicate that. The frame must undergo testing in addition to the typical high mass and high velocity impact tests, 2.0 mm High Impact lens must be retained by the frame.

4.3.2 New Development of Goggles

Military persons always get the most advanced PPE. Many new military goggles are developed, but more likely as an integrate system, like night vision goggle, holographic goggle and pilot goggle et al. But there do have some other developments in civilian level that is in the sun, wind and dust (SWD) goggle field. Here are five meaningful advancements [18]:

1. *Anti-fog lens coatings*: Anyone who has worn a goggle during strenuous activity will testify that fog resistance is one of the most important qualities in this product category. Minimizing condensation requires the goggle lens to have an effective chemical anti-fog coating. Several types of coatings are available in the commercial market--some more effective than others. An uncoated lens is far more susceptible to fogging, which seriously can impair the wearer's vision. A simple test can tell you if a lens is anti-fog treated: Just exhale on the lens--if it fogs up, the lens probably does not have an anti-fog coating.
2. *Large, filtered ventilation ports*: Sports-goggle experts long have recognized that another key design element in the battle against fog is adequate ventilation. High airflow can dissipate humidity that otherwise would condense as fog on the lens. The most fog-resistant modern goggles have large ventilation zones, and larger air

volumes inside the frames maximize airflow and minimize condensation. It is important that vents are filtered fully to keep eye-irritating particles outside the frame and away from the eyes.

3. *Comfortable anatomical fit and rapid strap-adjustment systems*: A key feature in goggle performance is a sealed, comfortable fit. Goggles that are uncomfortable due to gaps, pressure points, or improperly adjusted straps will not protect the eyes against blowing dust and smoke. In this case, Sailors or Marines may not use the goggles--even in hazardous places. High-quality goggles use a combination of anatomical modeling and malleable face padding to provide a sealed fit that is comfortable to wear for long periods. High-memory elastic straps with convenient length adjusters ensure a proper fit.
4. *Wide field of view with ample fit over eyeglasses*: Modern goggles provide unobstructed peripheral vision and a wider field of view. The SWD goggle has a relatively narrow field of view and a small interior volume that affords minimal room for eyeglass frames. Goggle frames now are available that fit over eyeglasses comfortably or accommodate the use of a prescription-lens insert.

5 Discussion

Using a real human subject is needless to say time and money consuming, and the individualities between subjects to subjects will obviously cause the final products are not suitable to part of their users, which maybe life-threatening in some cases. Real human test is also not practical in the impact experiments, like helmet test. Using a digital human head model to test the PPE will greatly help the designers.

There do have a number of well established digital head models, however, these models only mechanically consider the structure of a human head, more likely the skull and brain properties, but do not involve the face anthropometry and facial tissues. They are good for simulating the rigid impact of the head and possible injury, but lack of accuracy in design of some face-wear head protect equipments like respirators or goggles. Using the respirator TIL test as an example, the short coming of this test is using real human subjects. Though the facial sizes of these subjects are chosen to be approximately distribution of the whole working population in U.S, it is still not accurate enough. The individualities and the un-uniformity of movement even during one subject's test procedure aggravate this inaccurateness. Another defect is: you do not know which air path causes the seal leakage, is that because the interface pressure between the respirator and the user or the ineffectiveness and breakthrough of cartridge? Further researches will considers using the Principal Component Analysis (PCA) method and dates from the NIOSH survey to build a digital human headform which represents the facial Principal Components of the U.S. worker population. The new headform will have different catalogs of exterior size .Then we can use this headform, combining with the finite element method to conduct the visual test of the PPEs. For example, a finite element analysis will greatly help these goggle manufacturers to retest their products then make sure they are compliant with new standard or have to make changes as necessary.

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